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Theoretical Studies of Time Dependent/Independent Radiative Transfer Including Inelastic Scattering for Both Active and Passive Sources in Realistic Atmosphere-Ocean Systems

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13. ABSTRACT *(Maximum 200 words)*

The long term goals of this project were to obtain a thorough understanding of the behavior of the complete Stokes both within the ocean and in the atmosphere as well for both elastic and inelastic scattering for both active and passive sources. Specifically, we examined how one could use polarization information to obtain more information about the IOP's of both oceanic and littoral zone constituents. Asystematic study was also made of the neutral points in the atmosphere-ocean system for both reflected and transmitted radiation.

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A. Long-Term Goals

1. General:
Long term goals are to obtain a thorough understanding of the behavior of the complete Stokes vector both within the ocean and in the atmosphere as well for both elastic and inelastic scattering for both active and passive sources. Specifically, we want to see how one can use polarization information to obtain more information about the IOP's of both oceanic and littoral zone constituents.

2.Specific:
The development of a vector Raman-Brillouin radiative transfer code for realistic oceans in order to study non-stationary multi-spectral lidar and the effect of multiple scattering on the various AOP's.
There are several new goals we would like to achieve one of which is the use of circular polarization techniques to measure both the temperature and salinity as a function of depth.

We also wish to explore what information can be obtained from the new co-polarized and cross-polarized patterns seen by researchers in areas ranging from tissue optics to cloud lidar.
We are also developing a complete set of codes to calculate the Mueller matrix for electromagnetic scattering from irregularly shaped particles which will be used as input into our Monte Carlo codes.

We have also received a CRDF grant to begin a truly collaborative program with the group in Minsk headed by Dr. Eleonora Zege. We will try to utilize some very recent and powereful mathematical theory developed by the Belarus group into creating more efficient and robust Stokes vector radiative transfer codes.

B. Scientific/ Technical Objectives

It has now become infinitely clear in, the light of recent measurements, that polarimetry can be used to tell a great deal about the IOP's of ocean water. One of our major objectives is to find which elements of the Mueller matrix have the largest effect on specific components of the Stokes vector. The different structures of the scattering matrices in the case of marine organisms should lead to major differences in the circular polarization when compared to the results of calculations using spherical scattering centers in a hydrosol model.

We also would like to explore the possibility of using Raman circular depolarization techniques to determine temperature and salinity as a function of

depth. This information will be invaluable in speed of sound determination and will also be useful to physical oceanographers who need accurate density data for ocean models.

We are beginning a collaborative program with the Radiative transfer group in Minsk, Belarus headed by Dr. Eleonora Zege. Our objectives are as follows:
a) Simplification of the equations for the elements of the Green's matrix for the VRTE. Development and testing of an algorithm and code to compute the Stokes vector in an atmosphere-ocean using the Multicomponent approach (SVM-code).
b) Computation of the polarization characteristics of the light field in the ocean and atmosphere under solar illumination employing Monte-Carlo and SVM codes. Comparison of results and elucidation of ways to improve both codes.
c). Development of the simplified equations for propagation of a linearly polarized beam in order to study the Stokes vector in the on-axis region for both backward and forward directions.
d) Development of the code to compute the Stokes vector in the on-axis region for a polarized narrow beam and compare with experimental data.
e) Improving the codes for computation of the polarization characteristics of the light field in the ocean and atmosphere under solar illumination. Computation via improved codes. Data comparison.

C. Approach

In order to calculate the precise location of neutral points requires Stokes vector calculations at precise angles with **no bin** averaging. We have developed a new Monte Carlo method which uses statistical estimation to do precisely this. We have also developed a time-of-flight lidar code using the same techniques to calculate the complete Stokes vector for any source direction and position as well as any detector position and field of view. This is critical in predicting the positions and behavior of neutral points which form near the sun for an observer above the water surface. It has also allowed us to begin a systematic study of the Arago neutral point which appears near the anti-solar point as the sun sets. Since our method allows us to include all the effects of aerosol, Rayleigh, and hydrosol scattering with the additional factor of wind-ruffling at the boundary, we are able to explore the possibilities of using polarimetric observations of the passive solar light field for remote sensing.These codes will be used as tne nucleus for our collaborative effort with the Belarus team. We will then try to merge the methods developed by the Belarus team with ours to create state-of the-art vector radiative transfer codes for ocean modeling.

Development of a sophisticated Monte Carlo code that uses convolutions to evolve the frequency profile of the photons to handle both Raman and Brillouin scattering.

We now have running the DDA (Discrete Dipole Approximation) code obtained from Princeton. We are making modifications to it to handle some special cases as well as reformulate the theory into a resolvent kernel method which will make orientational averaging much easier.

We have developed a higher resolution Monte Carlo code for studying the finer structure in the polarization state of scattered light in an atmosphere-ocean system. Using our bulk Monte Carlo codes which solve the complete polarized equation of transfer for the full observable solid angle at any height above or below the ocean surface we are able to isolate regions of interest and to then apply our Monte Carlo with estimation techniques to these smaller areas.

We have also applied estimation techniques to the observation of polarization anisotropy in the backscattered light of a laser beam incident on a solution of Mie type scatterers. Our Monte Carlo code has produced images capturing all the qualitative features of observed phenomena so far reported in the literature. Our analysis shows that it may be possible to remotely determine particle sizes and concentrations by use of a system of polarizing analyzers and an active laser source. In the development of our code we have also shown that circularly polarized light has a longer "memory" of its initial polarization state than linearly polarized light and reflects interesting characteristics of the scattering medium. This persistence of circular polarization suggests that circularly polarized sources will allow observers to determine the characteristics of scattering particles deeper in the ocean than is possible with linearly polarized sources.

D. Tasks Completed or Technical Accomplishments

We have used our multiple scattering inelastic scalar radiative code with unique handling of the photon frequency distribution in order to investigate multiple scattering effects on the lidar return signal in a medium where both Raman and Brillouin scattering are taken into account. Results of this study will appear in the special SPIE issue being prepared by Victor Feigels.

We have also written a code to generate images of any polarization quantity in the complete observable solid angle. This has allowed us to present the data for any polarization quantity in all directions in one set of two images and to generate MPG movies showing the evolution of various polarization quantities as functions of changing model parameters. These images and movies are invaluable tools for understanding the processes of radiative transfer in the atmosphere-ocean system.

We have modified the DDA code to produce a scattering amplitude matrix from which Mueller Matrix elements could be derived. This was accomplished with no difficulty and further tests were run on spherical targets. These data were compared to data from a Mie code, for identical targets, and were found to match them nearly perfectly. Upon completing these tests, we began investigating scattering from other target configurations; i.e. ellipsoids, chains of spheres and larger cubic targets. Also, we began to experiment with varying dipole separation distances in order to determine at what separation the individual scatterers begin to behave as a continuum.

E. Results

The strong absorption or rather the selective property of single backscattering limits the frequency profile to one Brillouin event. Although Raman events arent effected by scattering angle the large frequency shifts limit these to singular events also (only stokes event). Coupling the above results we find that the overall frequency response will be one Brillouin convolved with one Raman profile. This results in a Voigt profile which is centered at the Raman shift since the brillouin shift is on the order of 10^-3 nm . Hence, the frequency profile will yield the usual Brillouin spectra and the usual Raman spectra quite similar to the single scattering spectra. Two publications resulted from this study:

We have been able to show that the polarization patterns seen by using co-polarized and cross-polarized analyzers can be emulated by using incoherent scattering techniques.

F. Impact(s) for Science and Technology and/or Applications

We are now showing the huge payoff that can be obtained by using polarimetry in ocean and tissue optics. The application to obtaining accurate temperature and salinity profiles will lead to a much easier, cheaper, and more reliable way to obtain these quantities and will be extremely beneficial to the Navy

G. Transitions Accomplished and/or Expected

a) Migrate the Raman Monte Carlo code to a tissue model, or to the tissue models used for human eyes, the area where most of the clinical research of Raman spectroscopy in tissue optics is taking place.
b) Use of our new lidar polarimetric code to analyze the feasibility of using polarimetric techniques to monitor the glucose level in the blood non-invasively.

H. Relationship(s) to Other Projects

a) The results obtained from our spectroscopy codes will be used by Dr. Fry and his group to use in their project using Brillouin scattering to measure the speed of sound in ocean water.
b) The results we are obtaining from our polarimetric lidar code will be used in a joint project with Dr. Lihong Wang to study polarimetric characteristics of human tissue

III Statistical Information

A.List of publications:

1) Joelson, B. D. and Kattawar, G. W., “Multiple scattering effects on the remote sensing of the speed of sound in the ocean by Brillouin scattering”, Applied Optics, 35, 2693-2701, (1996)

2) Joelson, B. D. and Kattawar, G. W., “Multiple Scattering effects in lidar spectroscopy”, to appear in special SPIE issue edited by Victor Feigels

3) Adams, J and Kattawar, G.W., Neutral Points in the Upwelling Light Above and Beneath the Ocean Surface: to appear in Applied Optics (1996)

B. Number of Grad students, Post Docs supported more than half time

1) Number of graduate students supported (at least part time)__________ 3
2) Number of post-docs supported (at least part time)__________ 0
3) Number of other professional personnel supported (at least part time)__________ 0
4) Number of female grad students__________ 0
5) Number of minority grad students__________ 0
6) Number of asian grad students__________ 0
7) Number of female post-docs__________ 0
8) Number of minority post-docs__________ 0
9) Number of Asian post-docs__________ 0

C. Patents

none

D. Presentations/Briefings Given (Invited and Other)

1.Invited:

Kattawar, G.W., "Virtues of Spectroscopy and Polarimetry in Ocean Lidar" SPIE Ocean Optics XIII Halifax, Nova Scotia (Oct. 1996).

2. Contributed:

Adams, J and Kattawar, G.W., "Polarimetric Lidar Returns in the Ocean: A Monte Carlo Simulation SPIE Ocean Optics XIII Halifax, Nova Scotia (Oct. 1996).

E. Service on Committees, Panels, etc. outide own organization

Selected by Dr. Tim Coffey to serve on NRL Review Committee for NRL Oceanographic Programs at Stennis Space Center, July, 1996

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F. Honors/Awards received

1. Selected by Physics Dept. to present the University Lecture for 1996
2. Associate Editor, Journal of Geophysical Research: Oceans

G. Percentage of funds sent on to other performing organizations

zero